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Accelerator Production of Tritium (APT)

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S. Drell, Chairman
R. Briggs
R. Brodsky
C. Callan
R. J. Dietz
D. Eardley
D. Hammer
R. Hilley
J. Landis
J. Leiss
R. Muller
B. Richter
M. Ruderman
S. Treiman
D. Ward

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JASON
The MITRE Corporation
7525 Colshire Drive
McLean, Virginia 22102-3481
(703) 883-6997

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30 January 1992

Dr. William A. Happer
Director, Office of Energy Research
ER-1 7B-05A/FORS
US Department of Energy
Washington, DC 20585

Dear Dr. Happer,

I am pleased to forward to you the report of the JASON Panel on "Accelerator Production of Tritium (APT)". As requested, this report evaluates the practicality of using particle accelerator technology to start producing the reduced goal quantities of tritium at the delayed start-up date of 2005 A.D.

The JASON APT Panel included scientists and engineers with a broad range of experience in accelerators and nuclear reactors, both in theory and in the development and construction of complex technical systems. It reviewed the documentation and was briefed in detail on the proposals for APT by the Brookhaven, Los Alamos, and Sandia National Laboratories. For further in-depth evaluation of the individual proposals, and in preparing this report, the APT Panel divided itself into two sub-panels which concentrated on technical and safety issues of the accelerator and the target subsystems, respectively. It is on these issues that our report focuses.

The APT Panel believes that APT is a technology that appears to be feasible and practical for producing tritium in the quantities specified by, and with a start-up date consistent with the currently projected national goal, and recommends including APT in the Programmatic Environmental Impact Statement (PEIS) for the new weapons complex. We support an R&D demonstration and test program, focused on engineered safety features, to supply the detailed information necessary to support and quantify conclusions on the safety, environmental impact and cost of APT. This program should be organized and performed cooperatively by the national laboratories.

The APT Panel also briefly reviewed the requirements and costs of electrical power for an APT system, but we have little to add to the assessment of the ERAB Report of February 1990 on this issue. As that report summarized, "the design concept for the continuous wave RF APT facility is at an early stage of development and will continue to evolve during the research and development program. Cost estimates are therefore uncertain, and are based on experience with constructing and operating smaller facilities with different operating characteristics". The JASON APT Panel had neither the time nor data to make an independent assessment of the ERAB Report's rough estimate that the capital cost of an APT system would range from $4.5 billion to $7.0 billion, except to note that it should be reduced somewhat as a consequence of the reduced production goal. It will clearly be of importance to refine estimates of electrical power

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availability as well as power requirement and both capital and operating costs as the design work progresses in order to determine whether the reduced goal for tritium production tips the economic factors in favor of APT. The cost of the R&D program presented to the APT Panel by the National Laboratories to provide the information needed is estimated to be roughly $70 million over the 18 month period between now and the August 1993 date of the ROD.

I hope you find this report of use. Best wishes.

Sincerely,

Sidney Drell

Sidney D. Drell
Chairman, JASON APT Panel

SDD/jgh

Enclosures

JSC-92-0101

Contents

1 EXECUTIVE SUMMARY

On December 24, 1991, the Secretary of Energy requested Dr. William Happer, Director of the Office of Energy Research, to "evaluate the feasibility and practicality of producing goal quantities of tritium using particle accelerator technology." The Secretary stated specifically that this evaluation "should be based on .... analyses of existing proposals and studies and on detailed briefings from accelerator proponents and others" and asked that a report of the findings and recommendations be submitted to him by February 21, 1992. The specific charge is shown in Appendix A.

At the request of Dr. Happer, a JASON Panel on Accelerator Production of Tritium (APT) was formed early in January to undertake this assignment. This report presents the Panel's findings and recommendations.

Two reasons motivate undertaking this review now, so soon after the February 1990 report of the Energy Research Advisory Board (ERAB) on Accelerator Production of Tritium:

1. There is continuing interest in APT because, as remarked in the ERAB Report, the "lack of uranium, plutonium, and fission product inventory; the low residual radioactivity and heat; the low operating temperature and pressure; and the ease of rapid shutdown" suggest that "an APT system is an attractive option in terms of safety, environmental impact, and public acceptance".

2. The goal quantity of tritium production has been reduced to between three-eighths and one-half that set previously; the date set for initiation of new tritium production has been delayed by five years from 2000 AD to 2005 AD; and, since February 1990, there have been advances in understanding the technology of both the accelerator and the target components of an APT system.

The focus of this report is on the technical and safety issues of an APT system sized to meet the new production goal. In view of the great uncertainties and continuing rapid changes in the world political scene, we have decided to comment also on how an APT production system might respond to future changes, either up or down, in the tritium production requirement. The Panel believes that APT is a technology that appears to be feasible and practical for producing tritium in the quantities specified by, and with a start-up date consistent with, the currently projected national goal and recommends including APT in the Programmatic Environmental Impact Statement (PEIS) for the new weapons complex. We support an R&D demonstration and test program, focussed on engineered safety features, and performed cooperatively by the National Laboratories to supply the detailed information necessary to support and quantify conclusions on the safety, environmental impact and cost of APT.

Technical issues and safety risks are well understood for the accelerator and beam transport components of the system. However, quantitative estimates of cost, efficiency and availability can only be made in the light of a detailed reference design. By this we mean a design that is <u>not</u> optimized, but which exhibits conceptual features constituting a feasible design from the point of view of known physical and engineering considerations. Thus, a reference design can form the basis of safety analyses and decisions as to feasibility, but the assumption should be made that further optimization could reduce costs and improve engineering features. We recommend that such a design for the accelerator system be developed as soon as possible.

Development of a design for the target system of the APT is less advanced than for the accelerator itself. Two very different proposals, both with considerable flexibility, were described to the Panel. Key issues of safety and efficiency for the more-conservative Li-Al target can be resolved by the ROD date if addressed promptly. The country already has considerable experience at Savannah River with this technology, both for fabrication of Li-Al targets and tritium extraction, but the irradiation environment for APT will be significantly different, requiring study of source terms, tritium retention in the target, operating characteristics of the accelerator (particularly the frequency of beam cycling), and materials properties. The newer and more innovative ^3He gas target offers the potential of significant safety and operational advantages, including continuous processing (which assures that there are only a few grams of tritium in the target system at any one time), ease of fabrication, and the absence of possible metal-water reactions in the event of a temperature excursion. Because of the importance of these potential advantages, development of the ^3He target should continue until a decision can be made as to its practical merits relative to the Li-Al design, even though a resolution of several key safety and operational issues probably will not be achieved by August 1993.

We recommend support for continuing design activities, including accident and safety analyses, on both target concepts. A decision between them should be possible within a year of the scheduled ROD date. Depending on the outcome of the R&D program there may be merit in continuing beyond that date with further design work on both the ^{3}He gas target and Li-Al design. The accelerator design is very largely independent of the choice of target and can proceed before such a decision is made.

We strongly encourage the National Laboratories to pool their APT efforts into a cooperative program, especially on the target design where most of the uncertainties reside.

2 INTRODUCTION

On December 24, 1991, the Secretary of Energy requested Dr. William Happer, Director of the Office of Energy Research, to "evaluate the feasibility and practicality of producing goal quantities of tritium using particle-accelerator technology." The Secretary stated specifically that this evaluation "should be based on .... analyses of existing proposals and studies and on detailed briefings from accelerator proponents and others" and asked that a report of the findings and recommendations be submitted to him by February 21, 1992. The specific charge is shown in Appendix A.

Dr. Happer, in turn, invited JASON to conduct this study and a JASON Panel on Accelerator Production of Tritium (APT) was formed early in January to undertake the assignment. The Panel members are listed in Appendix B.

The APT Panel met at the JASON Winter Study in La Jolla, California, during the week of January 13, 1992. The first morning was devoted to a review of the production accelerator requirements established by the Department of Energy and to a discussion of the charge to the Panel. James M. Broughton, Chief Engineer in the Office of New Production Reactors, reviewed and clarified the requirements and numerous provisions of the draft Production Accelerator Requirements Document which had been included in the material previously distributed to the Panel.

Monday afternoon and early Tuesday were devoted to a detailed briefing on the scheme developed at Los Alamos National Laboratory (LANL) for an APT system using a continuous-wave (CW) radio-frequency (RF) linear proton accelerator and an ^{3}He gas target. This was followed by a similar briefing on the Sandia National Laboratory's proposal, which is based on a pulsed-power linear induction proton accelerator. The day was completed with a briefing on the Brookhaven National Laboratory (BNL) variant of the continuous-wave RF accelerator using a Li-Al production target based on tritium-production experience with reactors.

On Wednesday the Panel members and representatives from the National Laboratories broke up into three sub-groups to explore details of the proposals for the accelerator design, the ^{3}He gas target, and the Li-Al target.

The first draft of this report was prepared by the Panel on Thursday, Friday, and Saturday.

Two significant changes have been announced in the nation's requirements for tritium since the ERAB report of February 1990:

1. As a result of recent political developments, particularly the signing of the Strategic Arms Reduction Treaty (START) in July 1991 and President Bush's unilateral initiatives of September 27, 1991 to further reduce the country's nuclear arsenal, the goal quantity of tritium production has been reduced to between three-eighths and one-half that set previously.

2. With the envisaged decrease in the US nuclear arsenal that, among

other things, allows the mining of larger quantities of tritium from withdrawn weapons, the date set for initiation of new tritium production has been delayed by five years from 2000 AD to 2005 AD.

These changes are the rationale for the Secretary's request and they open the door for a reconsideration of the potential for APT to be a reasonable alternative to a New Production Reactor (NPR). The questions to be answered are: Is APT competitive for the new reduced goal? Can basic safety and technical questions be answered in time to judge its potential by the date of the scheduled Record of Decision (ROD), now set for August 1993?

We address these questions in this report, focusing primarily on the technical and safety issues related to the accelerator and the target systems separately, and to the overall system operation.

In view of the great uncertainties and rapid changes in the world's political scene, we consider the potential of APT to supply smaller or larger quantities of tritium than the current production goal. We also identify important safety and technical questions that may not be answered by the time of the ROD (unless the ROD is delayed as a result of further delays in the startup date for tritium production).

In these deliberations the Panel followed the general thrust of the DOE Requirements Document and attempted to provide DOE with the following information:

- A summary of the major technical issues that need to be resolved before accelerators can be considered a viable option for production of tritium.

- A summary of the R&D, engineering and testing/demonstration that must be done to resolve these issues.

- A judgement as to whether or not this work can be done in time to be factored into the 1993 ROD.

- A recommendation regarding the future role of accelerators in the production of tritium.

The ERAB report highlighted the large requirements and costs of electric power for an APT system meeting full goal requirements (as then defined) for producing tritium. We have nothing to add to their comments beyond noting that these requirements and costs are reduced proportionally with reduced production goals.

3 SAFETY AND ENVIRONMENTAL ASSESSMENT

The report of the Energy Research Advisory Board (ERAB) to the Department of Energy (DOE) titled "Accelerator Production of Tritium (APT)" dated February 1990 concluded that "an accelerator production of tritium (APT) system is an attractive option in terms of safety, environmental impact, and public acceptance." This conclusion was based upon the "lack of uranium, plutonium, and fission product inventory; the low residual radioactivity and heat; the low operating temperature and pressure; and the ease of rapid shutdown."

It is these purported advantages that are responsible for much of the interest in APT relative to a new production reactor (NPR). However, much of the detailed information necessary to support and quantify conclusions on the safety and environmental impact of APT is not available at this time.

In view of the importance of this issue we summarize here key general observations that can be made at this time on the safety and environmental impact of APT:

- The accelerator portion of the APT does not appear to represent a safety hazard. This is a result of the predicted low level of radioactive contamination and the fact that similar accelerators have been designed, built and operated for many years to self-protect by shutting down in the event of significant upsets. Furthermore, an accelerator system failure that does not shut down the accelerator will generally result in the beam not delivering its energy to the target.

- The two target concepts presented during the Panel review have different safety characteristics and may present different safety risks. This difference may be a significant consideration in the selection of a target design, but sufficient information is not yet available to assess this difference adequately.

- The targets have potential generic safety implications. The radioactive source term in the target results from the spallation process, the absorption of neutrons and protons, and tritium production. The magnitude and composition of this source term and its decay heat are not yet quantitatively determined. Calculations (reviewed by the Panel) indicate that the total non-volatile radioactive source term and the total decay heat will be less than or of the order of a few percent of that contained in an equivalent production reactor. The volatile radioactive source term, exclusive of tritium, is smaller than the corresponding reactor inventory by a large factor for both targets (roughly 8000 for the gaseous ^{3}He target).

- The APT concept does not use fission to generate neutrons and hence does not produce the high-level waste by-products associated with reactor operations. The APT targets do not contain radioactive actinides or fissile material and hence are free of criticality concerns. We assume here, and in the following, that, at the reduced goal set for tritium production, there is no need to construct and operate a new fission reactor to power the APT accelerator.

- The APT concept is compatible with many of the safety design features used in modern reactors, including, as appropriate, containment, confinement, defense in depth, redundancy, and passive engineered safety systems.

Accident scenarios have not been defined and evaluated for the APT. These scenarios would have to include the effects of the thermal and hydraulic design of the targets, the magnitude and decay of the shutdown power, potential metal-water reactions, etc. Analyses of such accident scenarios are necessary for preliminary safety evaluations.

Therefore, although it is possible to conclude from the Panel review that the APT concept may indeed be attractive from the point of view of reduced safety risks, we cannot now give a quantitative measure of the difference in safety relative to various proposed technologies for the NPR.

4 ACCELERATOR SYSTEM

4.1 Introduction and Summary

The proton accelerator required to drive a tritium production complex at the required production level must deliver hundreds of megawatts of beam power in a safe and reliable manner. Two candidate technologies were reviewed: a radio-frequency (RF) linear accelerator (linac) based on an extrapolation of the technology of the Los Alamos Meson Physics Facility (LAMPF) accelerator at LANL, and a pulsed-power linear induction accelerator based on technology under development at Sandia and Lawrence Livermore Lab. Of these, only the RF linac is a candidate meriting further consideration if a decision to proceed is to be made in the next few years.

Pulsed power technology has an intrinsic advantage only in the case that a very large ratio of peak to average power is required. Such is not the case here. In addition, the experience base with this technology is very limited and an extensive, multiyear R&D program[1] would be required to address issues of technical feasibility and beam stability. Thus Sandia and we both conclude that the pulsed power option is not a viable candidate for the accelerator at this time.

[1]Such a program could test the claim by scientists at the Sandia National Laboratory that this technology might be feasible and could be less costly than the continuous wave RF linac for an APT system designed to meet significantly higher tritium production goals than presently envisaged.

The situation with respect to the RF linac is quite different. There is a very considerable experience base and there has been significant technology development since the time of the ERAB review of '89 - '90. While there has been no direct funding for APT studies, the Strategic Defense Initiative (SDI) Neutral Particle Beam program and paper studies for accelerator burning of nuclear wastes have led to significant progress. In addition, RF power sources developed for electron accelerators give increased confidence in the feasibility of the tubes required for the RF linac. Furthermore, the new goal (roughly half that considered in the ERAB study) is of course less stressing of accelerator technology.

The RF linac design presented by LANL was made before the final determination by DOE of the goal for Tritium production, and was scoped at one-quarter of that of the ERAB study. We have discussed with the designers the appropriate modifications needed to meet the new goal and to address some concerns of our own. The reference parameters that we consider as an appropriate minimum risk starting point are given below. Basically, we have doubled the energy, appropriately adjusted the beam current and eliminated the injection funnel (a device for increasing current by combining the output of two separate injectors).

Beam Energy	1.6	GeV
Beam Current	125	ma
Beam Power	200	MW
AC to RF Efficiency	60	%
RF to Beam Efficiency	70	%
"Wall Plug" Power	500	MW

Injector: Single RFQ & Drift Tube Linac @ 350 MHz
Main Accelerator: Coupled Cavity Linac @ 700 MHz

We emphasize that this is surely not an optimized design, but rather the starting point for a reference design. By reference design we mean one which exhibits conceptual features constituting a feasible design from the point of view of known physical and engineering considerations. One should assume that further optimization could reduce costs and improve engineering features.

Our main conclusions are as follows:

- The technology base exists to allow the accelerator to be built with high confidence. An SDI injector and radio frequency quadrupole (RFQ) have already produced CW beam currents of 100 ma with an emittance (product of beam size and angular divergence) smaller than that required. The drift tube linac is an old technology. There are 20 years of experience with the coupled cavity linac at LAMPF. High-efficiency 1MW klystrons at 350 and 500 MHz have been in use for several years at electron storage rings, giving high confidence that the 1MW 700 MHz tubes needed for the proton linac can be built.

- Beam losses that threaten the integrity of the accelerator are not an issue. Present numerical simulations show no beam losses under normal conditions, but are not sufficiently accurate to show losses of less than one part in 10^4 per meter. "Hands-on" maintenance requires average beam loss to be less than 10^{-8} per meter, so an extrapolation is required. Experience at LAMPF shows average losses at the 10^{-7} per meter level, except at the transition regions. The APT accelerator should have a ratio of physical aperture to beam size larger than

LAMPF and can have special occasional, well-shielded collimators to pick up stray particles. We expect hands-on maintenance to be possible except at the special collimators.

- Transient behavior of the linac is an issue that needs further study. A heavily beam-loaded accelerator operating at such high power can only be operated with a complex set of sensors and multiple, interacting feedback and feedforward control loops. In particular, start-up and recovery from safety trips or routine klystron trips that can be expected from time to time requires a programmed start where beam intensity, RF power and RF phase are varied together in a nonlinear fashion. The required sensor technology exists. Feedback and feedforward systems are in routine use at many accelerators. However, quantitative understanding of a system this complex can only be obtained from a reference design which includes a thorough study of system operation and transient recovery systems. Such a design study has not been done, and should be done as soon as possible, to assure good operability and quick recovery from transients. This design study should also deal with the effect of accelerator transients on the power grid. The worst-case possibility of unbuffered multi-100 MW demand fluctuations is probably unacceptable and some sort of "step-stop" or rotary store may be called for.

- Accelerator shut-down in the event of a target fault is not an issue of concern as long as appropriate redundant signals of trouble can be generated from the target. There are many ways to shut down the accelerator if required. Specific mechanisms and their typical response times are: shut down of the proton source (microseconds), mechanical stopper insertion (milliseconds), pulsed magnets to "dump" the beam at a stopper (10's of microseconds), RF power trip (10's of microseconds), etc. It is common practice in high power accelerators to use several independent parallel systems.

- Experience with other large accelerators suggests that the proton linac could probably be built in a period of five years from the start of construction. Commissioning of the accelerator should take less than one year. This excludes commissioning time for the target, part of which can be done in parallel with work on the accelerator.

- Engineering R&D and prototype work have the potential to significantly reduce construction costs and/or operating costs. For example, the development of more efficient RF power sources like the Magnacon could reduce AC power requirements by 10-20 % for a given beam power. Given the long time to required availability (2005 A.D.) and the relatively short construction time of the accelerator, such a program is strongly recommended.

- Downward excursions in the required goal can be easily handled; upward excursions are more difficult. For reduced demand, the accelerator can be operated part time with a major saving in electricity costs. (Heavily loaded accelerators have a current at which they are most electrically efficient. Extended periods of operation below this current are uneconomical.) Alternatively, a decision to reduce production before the start of construction could be accommodated by reducing the length of the machine, thus reducing its energy as well as construction costs. Major upward excursions in production (viz, a factor of two) cannot be accommodated without extensive rework to the accelerator and its support systems. It is probably easier to build a second accelerator. A more modest surge requirement, say 25-30%, could be incorporated into the accelerator design.

- Electric power availability is an issue. Many large accelerators operate on interruptible power, and we see no reason that this accelerator cannot do so as well. About 10% of full power demand will have to be firm to keep necessary auxilliary systems operating and to allow a quick return to full operation. Interruptible power costs less than firm power and may be available at more sites.

4.2 Accelerator Issues

4.2.1 Technology Status

There is a substantial technology base to support the design and construction of an APT accelerator. Proton linear accelerators with pulsed beam currents of 100-200 ma and 100-200 MeV energy are used as injectors on all high energy physics proton synchrotrons. The average currents are low because of the pulsed operation. Continuous duty (CW) coupled-cavity linac structures and CW RF power sources have been developed for electron linear accelerators and high energy electron storage rings. These RF sources could be used for the APT accelerator but development of a new tube which is specifically optimized for the APT accelerator application might be cost-effective.

Research in the SDI program has made substantial contributions to the proton linear accelerator technology base. For the SDI application, preservation of beam emittance and brightness is vital, and analysis and design capability to preserve beam quality is well established. In particular, the causes of emittance growth within accelerators are now well understood. For the APT application this reduces concern about beam loss to the accelerator structure. In the SDI program, since the ERAB Panel report, routine CW operation of the low-energy end (ion-source and RFQ) of a proton linear accelerator operating at 100 ma has been demonstrated at Chalk River Nuclear Laboratory, Canada and a successful experimental demonstration of beam funnelling has been performed at LANL at 5 MeV, with no beam loss and without appreciable beam emittance growth.

The most relevant proton linear accelerator experience for APT is the 800 MeV LAMPF accelerator. LAMPF has been in operation for about 20 years, but contains most of the essential hardware and most of the control systems required for the APT. Although LAMPF has a much lower average beam current, its operating characteristics are quite similar to those of an APT accelerator: although it has a duty factor of only 6% and only one quarter of the RF buckets in a macropulse are filled, the peak beam current (or the charge per bucket) in LAMPF is only a few times less than in an APT accelerator. Consequently control and beam loss information derived from LAMPF is very relevant to the APT case[2].

4.2.2 Engineering, Design and Optimization Issues

In agreement with the ERAB Panel, this Panel believes that there exists an adequate base of experience and technology to give confidence that a successful APT accelerator can be built and operated with adequate availability and reliability. This conclusion is strengthened by technical developments since the ERAB Panel and by the recent reductions in production goals.

What is most needed now is development of a detailed reference design in which all pertinent design trade-offs and operational issues are considered and resolved. A serious funded effort to develop this reference design is a high priority need, and must be initiated if a credible evaluation of APT in comparison to other alternatives is to be made. In the discussion below we comment on a number of the engineering and optimization issues which must be addressed in this reference design.

To understand the issues for an accelerator which would have production capability at the new goal levels, the Panel considered a reference case of 1.6 GeV, 125 ma CW accelerator without funneling. We believe this accelerator could be built and is operationally simpler than an accelerator with funneling. Achieving the higher production capability for the newly defined production

[2]The early Materials Testing Accelerator (MTA) project at LLNL, that was designed to lead to accelerator production of plutonium, did provide experience for high-current CW operation (250 ma deuteron beams) at low energy (up to 7 MeV).

goal was done by increasing the beam particle energy from the conceptual case presented to the Panel by LANL. This keeps the beam current down, and, we believe, makes the target design less difficult. For the most part, the accelerator is the same as that considered by the ERAB Panel, but operating at one-half the average current.

The reference design effort which we recommend must make optimization trade-offs among various considerations. Beam funneling makes design of ion-sources, RFQ, and initial drift tube linac tanks less difficult, but adds a potential source of beam loss and complexity at the funnel. Beam particle energy and current trade-off influence the amount of beam loading, the construction and operating costs, and the target design.

Beam loss in the accelerator is an important design consideration. In normal operations, beam losses should not endanger accelerator components, but could influence residual radioactivity. The LAMPF experience, and the ability to model this experience, indicates that with the design measures proposed by LANL, hands-on maintenance of the accelerator should be possible, except perhaps for a few hot spots. Careful attention to beam optics design to avoid emittance growth and keeping the beam much smaller than all apertures is required. The APT accelerator designs keep the ratio of acclerator aperture to beam size substantially larger than in LAMPF, which should ensure greatly reduced beam losses to the structure. Accelerator alignment and RF power control tolerances will be determined largely by these requirements for minimum beam loss. The possibility of beam losses to the accelerator during turn-on and interruptions will be discussed below.

RF control to tight tolerances is required. Sophisticated control systems have been developed for LAMPF and other proton linacs and for the SDI program. They maintain accelerator resonance frequency through structure temperature control, and succeed in controlling RF fields in the accelerator cavities to about 1 percent in amplitude and 1 degree in phase in spite of substantial loading of the cavities in phase and amplitude by the accelerator beam. Although the requirements for the APT accelerator are very similar, the higher beam loading, the CW operation, and the requirement for fast recovery from transient faults will require special consideration in the APT design. The ability to properly handle all of the turn-on and transient situations which might occur will influence how much control margin must be left on RF klystrons, and therefore klystron operating efficiency. The Panel believes that the 3% control margin used by LANL in their scoping designs is not adequate and should be increased to 5%.

Accelerator availability will be determined by component failure rates and by the time spent in recovery from transient upsets. The components most likely to fail are ion sources, RF windows, and klystrons. Conservative designs are required, but some failures can be expected. In many cases, these components can be replaced during routine maintenance periods in anticipation of end-of-life. In the system design, care should be taken to minimize the time to replace these components. In many accelerator installations klystron lifetimes of many tens of thousands of hours have been observed, so that klystron failure rates should not be a serious operability issue.

Transient upsets must be considered as a normal operational occurrence and must be designed for. The principal upsets anticipated are brief interruptions or changes of the beam current from the ion sources, and a brief interruption or fault of an individual klystron. Because of the large number of klystrons in the APT accelerator, one must anticipate several (perhaps 10) such interruptions per day. After initial system shakedown, most such interruptions will be momentary, and the system can rapidly be brought back to operation. However, because of the high beam power of the APT accelerator, most such faults will require that the beam be interrupted and brought back on again in a controlled and standard manner. In such a start-up, the RF fields in the accelerating cavities will be held at the correct amplitude and phase by their individual control loops and when all cavities are at the correct field, the proton injector will be turned back on with rise time slower than the slowest control loop in the RF system. Recovery from most such transient faults should occur in a few seconds[3]. Thus even though there may be several of these per day, they should not greatly influence the accelerator availability. Recovery from faults requiring change-out or repair of components will take longer, but these will be less frequent.

The above discussion illustrates the principal issues which must be faced in the design of a control system for the APT accelerator A further complication is that the accelerator control system must be coupled to those of the beam transport system and the target facility. It should be noted that there is a broad base of experience for the design of these control systems. Sophisticated computer control systems are used extensively on most large accelerators, including LAMPF, which, as noted above, has peak current

[3]If unbuffered, these transients could impose rapid multi-100 MW demand fluctuations on the power grid. Damping systems may be needed.

comparable to the APT accelerator. What is needed is an APT accelerator reference design constructed with special attention to the high beam power and the need for high availability. The design should be elaborated in sufficient detail to ensure that all important off-normal situations have been considered and designed for.

4.2.3 Safety and Environmental Issues

The power in the beam of many large accelerators is great enough that beam impingement in the wrong place could burn out and destroy components in a few seconds. The APT accelerator beam power is very large (about 200 MW) and therefore safety issues are even more important. Beam interruption is required at any time an improper operating situation is detected, either in the accelerator itself, in the beam transport between the accelerator and the target system, or in the target system. Given a turnoff signal, the beam can be interrupted in a few microseconds. Many redundant signals are available. In the accelerator these include: out of tolerance change of ion source current; detection of improper RF field, phase, or reflected power signal on any cavity; loss of beam transmission from one point along the accelerator to another; detection of large radiation generation at some point in the accelerator tunnel; detection of poor vacuum; etc. In the beam transport between the accelerator and the target, fault signals include improper magnetic fields, beam loss to beam scrapers, or inadequate spreading of the beam at the target. Protection against such failure modes is routine on most accelerators. A passive detector to prevent excessive beam density at the target window could be as simple as a fusible ribbon which would fail by melting and cause beam interruption before window failure.

Several fast valves should be included in the accelerator and between the accelerator and the target window. Any detection of improper vacuum would cause these valves to close. Adequate distance should be allowed between the accelerator and the target area to ensure that these valves are closed before any shock waves from a window failure reached the accelerator. Fast valves with appropriate performance are used on many accelerators.

Windows and their possible failure modes have a critical effect on the operational and safety characteristics of an APT system. Extensive experience at particle accelerators with the performance of windows subject to intense charged particle beams gives assurance that failure of the accelerator window will not be a problem. However, the target window may be subject to heavy neutron flux and operate in a regime for which there is much less direct experience. Calculations by LANL indicate that damage to the target window will in fact be dominated by the effects of the direct proton beam so that, once again, window failure should be a rare problem. Careful study of this issue is obviously in order.

Standard accelerator shielding design will be adequate to provide personnel radiation safety outside the accelerator vault for any level of beam losses. The air within the accelerator should not be vented during operation. Cooling water systems which might have radioactivity should be backed up by secondary loops to ensure that all activity is contained.

The principal radiation issue in the accelerator is the question whether hands-on maintenance is reasonable or whether remote maintenance is required. As discussed earlier, the LAMPF experience, together with the design features proposed by LANL, indicate that hands-on maintenance will be possible for most of the accelerator, with perhaps remote maintenance required in a few places. This same conclusion was reached by the ERAB panel. The reduction of a factor of two in the goal quantity, and the consequent reduction in design beam current adds confidence to this conclusion.

4.2.4 Excursions in Production Requirements

The tritium production goal quantity is the production capability which must be available to satisfy the largest credible demand. The goal quantity has recently been reduced by a factor of two from the goal levels considered by the ERAB Panel. It is prudent to consider the impacts if the goal level should be further reduced, or if the production requirements should turn out to be less than the goal production capability level. We distinguish design changes which would occur if goal levels should change before an accelerator were built from the performance of an already built accelerator at reduced production requirement.

If goal levels were to be reduced by a factor of two from present levels before construction, the APT accelerator design would first probably reduce beam energy down to about 800 MeV (corresponding to the scoping design presented to the panel by LANL) with a proportionate reduction in the accelerator capital and electric power costs. Further goal reduction would be accommodated by reduction in design current or by reduction of operating schedule to utilize off-peak power rate savings.

For reduced production after an APT accelerator were built, accommodation to reduced production requirements would be most economically accomplished by operating at reduced schedule to take advantage of off-peak power rate savings. An option would be to develop a second tritium producing target assembly at a lower energy point along the accelerator. Because of the domination of electric power costs in the total operating cost, the cost reduction would be close to proportional to the production requirement, with perhaps further improvement due to use of off-peak power.

For increased production, the situation is more complex. Accelerator construction costs in the APT case are dominated by the cost of RF power. Doubling the yield, for example, would require doubling the installed power base, doubling the number of klystrons, replacing the injector, perhaps replacing the targets, etc. In this case it is probably simplest to build a second accelerator and target complex.

4.3 Recommended Program

In the near term, the most urgent task is the development of a reference design for the (new goal) tritium production capacity. This design activity should include detailed analysis of the operational features of the accelerator system including such items as:

- The beam turn-on process, including responses to transients, describing how the phase and amplitude of the accelerating fields in the heavily beam-loaded RF cavities are maintained as the beam current is brought up.

- An assessment of particle losses in the accelerator that can lead to activation of components and affect the "hands-on" maintenance protocol. The losses during the turn-on processes should be included in this assessment.

- The beam abort systems that protect the accelerator and target from damage when there is a malfunction that would lead to localized beam losses. The control of several hundred megawatt beams is a critical aspect of the APT concept. Conceptual approaches, and experience from current high power accelerator facilities, suggest this can be done, but the overall implications on the system design must be described in detail.

The reference design activity should be closely integrated with the need for input into DOE's Complex-21 Programmatic Environmental Input Statement (PEIS) (assuming the APT system is included in this document). Knowledge of many technical and operational features of the reference designs are essential for the PEIS to accurately represent the APT option, and the schedule for producing documentation in environmental safety and health (ES&H) areas needed for the PEIS is very tight.

Another important output of the reference design activity is an improved cost estimate.

In the pre-construction phase, effort should go into those component engineering developments having the greatest leverage on the reliability, maintainability and cost of the overall system. Foremost in this category is the RF system, and the RF sources and RF windows in particular. Other engineering development and prototyping that can impact selections among the technical options include further tests of the low energy systems and the beam splitter at the high-energy end of the accelerator.

The current DOE schedule calls for production capability in 2005 A.D. Since the construction of the accelerator facility requires about five years, and a year is reasonable for commissioning, there is ample time for engineering development and design optimization. The front-end region of the accelerator and a section of the coupled-cavity linac should be assembled from prototype components to gain experience with the operation of an integrated system at high power levels. In our view, a decision to begin construction of an accelerator could precede results from this front-end test, although early results from this testbed would clearly be desirable since it would provide additional assurance in the technology.

5 TARGET ISSUES

5.1 Target Description

Development of a design for the target system of the APT is less advanced than for the accelerator itself. Two very different designs, both with considerable flexibility, were described to the Panel. The target must serve two functions: first, to convert the energetic protons from the accelerator into a multitude of neutrons by spallation of, and evaporation from, heavy nuclei such as lead or tungsten; and, second, to form tritium by nuclear interactions initiated by these neutrons. Because both of the target concepts presently being studied benefit from having thermal neutrons rather than the energetic neutron spectrum characteristic of the spallation process, both targets require neutron moderators. Two different light target isotopes are being considered for producing tritium with the thermal neutrons. The first, ^{6}Li, has been used historically in reactor production of tritium[4]. The second, ^{3}He, the stable decay product of tritium, has not been used in previous production systems but is available in sufficient quantity[5]. The moderators considered were light water (H_2O) and heavy water (D_2O).

A target system can be designed somewhat independently of the acceler-

[4]A thermal neutron incident on the isotope ^{6}Li produces T plus ^{4}He with a cross-section of 941 barns

[5]A thermal neutron incident on the isotope ^{3}He produces T plus a proton with a cross-section of 5330 barns

ator. Although the target must be compatible with, and should be optimized to, the characteristics of the proton beam, particularly its energy, current and geometric size, a variety of configurations and process arrangements are possible. The tritium can be removed from the target system in batches or as a continuous stream with on-line extraction of product tritium [6].

The first of the two target system designs described to the Panel is an adaptation of the lithium-aluminum target technology used for 35 years with the Savannah River production reactors. The second design, which makes use of ^{3}He gas, is more innovative and offers possible operational, safety and environmental advantages, but is at an earlier stage of development, implying greater technical uncertainty. Not enough resources have gone into the study of either of them to be sure what they will look like in an APT system reference design. Therefore, it is here that the most can be accomplished in terms of reducing uncertainties and increasing confidence in judging APT as an alternative to an NPR.

The degree to which the safety and environmental advantages of APT make it an attractive alternative to a nuclear reactor depends upon the details of the target design. The lithium-based target design described by Brookhaven scientists is sufficiently advanced that it is already possible to carry out preliminary safety analyses and accident assessments. In the innovative ^{3}He based design described by Los Alamos scientists, it is still necessary to first complete a conceptual design of the target and then a detailed mechanical design, including specification of the materials to be used, so that

[6] Tritium β-decays to ^{3}He with a half-life of 12.36 years; 5.6% decays per year.

proper safety analyses and accident assessments can be done. The accelerator design is independent of the specifics of the target, requiring only that the final beam-transport system be designed to spread the beam over the area desired for the target. Therefore the choice between the two target design concepts should be based upon a determination of which one minimizes risk (both technical and with respect to health, safety and the environment) and which one has the best cost and operational characteristics. We believe it would be advantageous to continue design activities, including safety and accident studies, on both target concepts until the ROD. Specifically, the potential additional safety and operational advantages of the ^{3}He target justify its continued study even if the Li-based target were to be judged to be acceptable for an APT system at the time of the ROD.

5.1.1 ^{6}Li Batch Processing Design

This design, presented by the BNL group, would use arrays of lead and lithium-aluminum rods clad with aluminum, each about 1 cm in diameter and 150 cm long. About 500 rods would be contained in each of several aluminum housings, 30 cm in diameter, arranged in rows perpendicular to the proton beam. Several rows of housings would be located along the length of beam travel. A target chamber, with a beam window two meters in diameter[7], would contain the target array and associated piping, shielding, and reflectors. Light water would be pumped through each target housing where it

[7]The failure characteristics of this window are obviously critical and must be studied carefully. See the remarks on windows in Section 4.

would moderate spallation-produced neutrons and remove heat generated in both the lead and lithium-aluminum rods.

This target system relies heavily on the tritium production experience and existing facilities at Savannah River. Thousands of lithium-aluminum and lead rods would be manufactured by methods similar to those used for many years in the manufacture of seemingly more complex reactor targets for tritium production. Batch processing of targets for extraction of tritium, including waste disposal, would be nearly identical to that used at Savannah River for reactor targets.

Although the lithium-aluminum target technology is based on the extensive fabrication and extraction experience at Savannah River, the irradiation environment in the accelerator target lattice is significantly different from Savannah River. The high proton flux (and its cycling on and off due to accelerator transients), the existence of spallation products, the difference in neutron spectrum, and the lack of significant gamma flux in the target means that the experience base of such empirically derived effects as tritium retention by aluminum cladding may not be directly applicable. In order to be sure that there are no unexpected effects, a test of target components should be carried out in an accelerator target environment of protons and with the appropriate spallation neutron spectrum.

Because of frequent sudden losses of accelerator beam power as a result of the trip-off of one of many klystrons (perhaps several times per day) the APT target could experience changing power levels between zero and 200 Mw for intervals of seconds to minutes up to 1000 times in a 6 month period.

The APT target designer must assess the potential challenge to target and system integrity from the thermal and metallurgical problems arising from such changes. This may require more frequent changes of the parts of the target system directly in the beam line.

Development of fabrication methods for lead target rods will also be necessary. Furthermore, irradiated lead is currently classified as mixed-hazardous waste and means for its safe disposal or reprocessing must be developed.

This design involves environmental and safety issues arising from the fact that the entire inventory of tritium produced is held in the batch of targets being irradiated at any one time. The large inventory must also be dealt with in the tritium extraction process. This processing approach is similar to that used at Savannah River for 35 years.

5.1.2 ^{3}He Continuous Flow System

This design presented by the LANL group would use a chamber containing banks of 1/16-inch tungsten rods surrounded by flowing ^{3}He gas. The banks of rods would be arranged perpendicular to the proton beam in several rows. Each bank of rods would be confined within an Inconel container. D_2O would flow through the container to serve as moderator and to remove rod heat. The target assembly would be surrounded by a D_2O moderator and reflector, and possibly a lead neutron-multiplying layer. A small sidestream containing ^{3}He and tritium would be continually removed from the target and blanket circulation system, then processed and re-injected. Tritium gas would be separated by a chromatographic process and impurities would be removed. Tritium would be in pure form and no further processing would be necessary. The existing tritium extraction facility at Savannah River would not be needed for this target system, because extraction is integral to the target system design. The continuous processing ensures that there is only a small inventory of tritium (several grams) in the target system at any one time, a considerable advantage should a serious accident occur. Other advantages of the ^{3}He target are ease of fabrication and absence of possible aluminum-water reactions in the event of a temperature excursion.

The specific target design described to the Panel was quite compact and as a result had very high thermal power density. Considerable engineering development would be necessary to provide appropriate fluid and heat transfer systems. However, it is apparent that the target system can be made less compact and adapted to a wider beam spread and that the power density can thereby be decreased by a factor of ten or more. This would permit a more straightforward thermal design and seems warranted. A larger target would require a larger window than the presently proposed design of 35 cm diameter. At the same time, the target pressure of 200 pounds per square inch which the window must hold against the vacuum in the beam pipe, and the cooling requirement would drop with an increase of target and window dimensions. This is one of the important technical and safety issues to be addressed by a reference and subsequent mechanical design.

The proposed ^{3}He design would use tungsten as a spallation target. This will present less of a waste disposal problem than would lead; however, the use of lead would probably have the advantage of increasing the tritium production efficiency by roughly 10%, a gain that may not be worth the added complication of having to dispose of mixed waste[8].

The gas circulation and purification systems for tritium recovery, as proposed, have not been previously used as a combined system in any manufacturing processes. However, the individual components have been developed and used extensively in tritium recovery and purification trains in the Tritium System Test Assembly (TSTA) at LANL, Savannah River (Bldg 232H) and the Mound Laboratory. Although these components have never before been integrated in the type of continuous processing system proposed for the APT, we do not consider that this poses a significant technical risk.

An APT group should complete a reference design for the ^{3}He target, followed by a mechanical design with sufficient detail that a safety analysis and accident assessment can be made. Furthermore, an experimental program to obtain data on neutron and spallation activation of the intended target materials should be initiated, again to provide information needed for the safety analyses and accident assessment. Finally, a prototype target should be built to obtain the neutrons per proton production ratio and, eventually, the tritium per proton ratio, to refine calculations of beam power required

[8]Removing the lead multiplying layer would also be desirable in order to avoid this complication and should be considered in designing the target. In the current design the lead layer adds roughly 25% to the number of neutrons – largely as a result of spallation due to scattered beam protons entering the layer.

to produce any given quantity of tritium, and to benchmark computer codes used for system design.

5.1.3 Feedstock Availability

The availability of ^{6}Li is not in question. Existing stockpiles far exceed any foreseeable requirements. The availability of ^{3}He also turns out not to be a significant problem. First, as LANL emphasizes, an ample supply of ^{3}He has been accumulated from decay of tritium, and this stock increases every year. If there are no irrecoverable losses of ^{3}He or tritium in processing or in the stockpile, then recycling of ^{3}He via APT suffices to keep the tritium inventory constant. However, losses could occur either through long term leakage or sudden accident. Moreover, an increase in non-weapon uses for ^{3}He (e.g., in neutron detectors or in the fusion program) could conceivably compete for this finite stockpile. Therefore it is prudent to look into natural sources of ^{3}He. Helium is available from certain natural gas wells, but the ^{3}He content is highly variable due to geology (such helium is often created as pure ^{4}He by α decay of natural actinides, rather than being primordial). In certain production areas, however, the ^{3}He abundance is high enough ($\gtrsim$ 1ppm) to support isotopic separation of ^{3}He; these include West Texas and the North Sea. Though expensive and limited by ordinary standards, these areas could provide an assured source of ^{3}He for APT and other applications.

5.1.4 Target Safety Issues

The use of lead and tungsten in the spallation targets leads to a yield of fission products that is several orders of magnitude less than that found in a fission reactor. In addition, other radioactive isotopes are created in the spallation reactions. Data on the quantity and character of these radioisotopes are not well developed but estimates have been made. For a target system capable of producing tritium at the same rate as in a thermal reactor, the decay power and total quantity of radioisotopes shortly after shutdown is estimated to be of order 1/50 of what it would be in a reactor. The quantity of volatile spallation products, exclusive of tritium, has been estimated by Los Alamos to to be only about 1/8000 of the reactor quantity. For the ^{3}He target, total volatile radioactivity, including tritium, is about 1000 times smaller than for a reactor due to continuous processing. For the Li-Al target, which relies on batch processing, total volatile radioactivity is roughly comparable with a reactor. In addition, there will be no actinides in either type of APT target assembly.

These estimated quantities of decay power and radioactivity, while substantially lower in the APT target than in a reactor, are not negligible. Reliable systems for shutdown emergency cooling and possibly containment will be required.

There appear to be a variety of highly reliable means to rapidly shut off the accelerator beam given any incident which would tend to cause overheating of the targets. Such incidents would include loss of cooling flow to the targets or transient misfocus of the beam. Thus it is extremely unlikely that emergency cooling systems will have to deal with other than removal of radioactive decay power which, as noted, is only a few percent of that in a reactor of comparable tritium production capacity.

A containment structure around the target system may be warranted by safety and environmental considerations. The required size and strength of such a structure cannot be determined until detailed safety analyses are available. The safety analyses are, in turn, dependent on information from a more complete design. A possible vulnerable point in a containment would be the necessarily thin window through which the proton beam enters the target assembly. Provision must be included for blocking off the window opening in an emergency, using isolation valves or dampers of the sort commonly used in modern accelerator beam transport or in containment systems for power reactors.

5.2 Comments and Schedules

If an APT system is to be competitive with a proven and reliable reactor based system, it will be necessary to develop some confidence that an APT system can meet desired safety and reliability criteria by the date of the ROD now scheduled in August 1993. Such a demonstration will require enough information to specify the source function for target radioactivity and support an analysis of the consequences of credible accidents. To gain confidence in reliability will require the realistic testing of components wherever these are different in kind or in their radiation environment from those used in past systems. This is especially important for radiation-associated metallurgical questions where the predictive power of present theories may be inadequate. All of the information needed to evaluate proposed APT systems is not yet available because research and development programs have not been funded. Some of it would probably take up to two years to acquire. Nevertheless if the APT option is included in the PEIS a much greater part of the crucial data and analysis should be obtainable within little more than a year or so after program funding is authorized, and so could be available for the presently scheduled August 1993 ROD. A complete analysis for the ^{3}He target might not be expected before well into 1994.

The proposed Li target employs aluminum-clad Li-Al solid rods of similar composition to those long used for tritium production in the thermal neutron flux of the Savannah River production reactors. There the produced tritium remained well confined by the clad Li-Al for more than six months of exposure to thermal neutrons. The main differences in environment for APT target rods are exposure to the energetic proton beam itself (and the possible effects of cycling that beam on and off), to spallation products and their secondaries, and the absence of a strong flux of γ-rays. Consequences of all of these could be simulated by exposure of Pb rods and H-loaded Li-Al rods to the Brookhaven AGS proton beam. Any indication of unexpected results, especially for the crucial issue of tritium retention in the rods until processing, should be apparent within much less than a year after the beginning of such a measurement program.

Because the ^3He target is more innovative and has unproven design features and components, it will require considerably more development and testing to achieve the same credibility and allow the same kind of target safety analysis as that which can be achieved for the Li-Al-Pb target. It is plausible that a preliminary conceptual design could lead to a mechanical design for the target within three months of the initiation of a design and test program.

The construction of a bare target model (without a surrounding neutron moderator and ^3He blanket) might take an additional 4 months. The target could be placed in the LAMPF Weapons Neutron Research facility where the low current 800 MeV beam could be used to determine the neutron yield and benchmark the codes within about 3 months of operation. In parallel, material sample tests could be carried out in the full LAMPF current at the beam stop. Before the ROD, these tests could reveal any metallurgical problems, and benchmark the codes allowing the source term to be pinned down to within better than a factor of two. All of this may then be available within little more than a year after the initiation of the design and test program.

The safety analysis could begin at the end of the first three months, after the mechanical design was produced. Source term calculations could take three months after that, and the safety analysis be completed about a year and a half after the start of the program. Predictive codes exist and should be refined and benchmarked by that time. The design, installation and initial testing of the moderator and blanket has been estimated by the

LANL group to take about a year. It may be expected that this first year to year and a half would be sufficient to learn if there are any great surprises. It would take about two years to complete the test program, which includes moving a complete target to the BNL accelerator for exposure to 1600 MeV protons. The ultimate design development and testing program for target systems should give attention to aspects that have presented problems in fission reactor development. These include often interdependent effects of thermal stresses, flow induced vibrations, coolant chemistry, and corrosion and radiation on target and system components. Design optimization is likely to require iterative development and prototype testing.

It is to be hoped that a year and a half of testing for both types of target systems could be accomplished before the August 1993 ROD date. This depends upon how soon the needed design and test programs can begin. The potential additional safety advantages of the ^3He target would justify its continued study even if the APT with a ^6Li target were already shown to be safer and no less reliable than reactor-based tritium production.

6 APT REQUIREMENTS DOCUMENT

The Department of Energy provided JASON copies of its Level I "New Production Reactors Mission, Objectives and Fundamental Requirements" (NPD-001) and a draft Level II Accelerator Requirements Document. The Level I NPD-001 document sets forth the fundamental and programmatic requirements for providing tritium production capacity. The Level II requirements were developed from the NPR requirements to assure that all technologies considered for tritium production are evaluated on an equivalent basis. DOE acknowledged that some of the Level II requirements may need interpretation with respect to their application to an accelerator.

As noted by DOE, the NPD-001 document was written to address reactor-based proposals. The modifications made so far have been mostly at the level of "word replace" in the original document, substituting "accelerator" for "reactor." In many places this makes for strange and irrelevant language. Furthermore, there has been little attempt to distinguish between the accelerator part and the target part of the APT system. In most places in the text the word "accelerator" has been used to represent the entire system. In other places the word "accelerator" really means just that, and distinctions are made between the target and accelerator subsystems. There is no consistency.

While we have not reviewed these requirements in detail we have the following comments:

- It appears highly probable that the safety and environmental objectives contained in this document can be achieved for the APT.

- Because of the unique features of accelerators and the proposed targets, the appropriate methods to achieve these objectives may not be consistent with the Requirements Document.

- The document should clearly distinguish between accelerator and target requirements.

We recommend that this document receive an in-depth review and the necessary rewrite to accommodate specific characteristics of APT. This task should include people with expertise in accelerators as well as other pertinent technologies. We recognize that this document, and the corresponding one for the NPR, will be very important in the DOE evaluation of the options for tritium production. Therefore the recommended revisions are important.

7 CONCLUSION AND RECOMMENDATIONS

7.1 Conclusion

We believe that APT is a technology that appears to be feasible and practical for producing tritium in the quantities required by, and with a start-up date consistent with, the currently projected national goal. This option also has a high degree of flexibility in responding to modest changes in schedule and production requirements.

7.2 Recommendations

The panel recommends including APT in the Programmatic Environmental Impact Statement (PEIS) for the new weapons complex. The National Laboratories presented to the Panel well-conceived proposals. There is every reason to expect that an appropriate R&D demonstration and test program can lead to the successful design of an operating system. This program, if adequately supported and successfully accomplished, would provide the basis for an informed decision by the scheduled date for the ROD on August 1993 as to whether the country should develop APT or proceed with a New Production Reactor if it is to meet its tritium-production needs (three-eighths to one-half the old goal quantity) starting in 2005 AD. The following are the key findings that form the basis for this recommendation:

- Technical issues and safety risks are well understood for the accelerator and beam transport components of the system. However, quantitative estimates of cost, efficiency and availability can only be made in the light of a detailed reference design, and we recommend that such a design be developed as soon as possible.

- Key issues of safety and efficiency for the more-conservative Li-Al target can be resolved by the ROD date if addressed promptly. The country already has considerable experience at Savannah River with this technology, both for fabrication of Li-Al targets and tritium extraction, but the radiation environment in the APT will be significantly different, requiring study of source terms, tritium retention in the target, operating characteristics of the accelerator (particularly the frequency of beam cycling), and materials properties. The newer and more innovative ^{3}He gas target offers the potential of significant safety and operational advantages, including continuous processing (which assures that there are only a few grams in the target system at any one time), ease of fabrication, and the absence of possible metal-water reactions in the event of a temperature excursion. Because of the importance of these potential advantages, development of the ^{3}He target should continue until a decision can be made as to its practical merits relative to the Li-Al design even though a resolution of several key safety and operational issues probably will not be achieved by August 1993. We recommend support for continuing design activities, including accident and safety analyses, on both target concepts. A decision between them should be possible within a year of the scheduled ROD date. Depending on the outcome of the R&D program, there may be merit in continuing beyond that date with further design work on both the ^{3}He gas target and Li-Al design. The accelerator design is very largely independent of the choice of target and can proceed before such a decision is made.

We also recognize that there is considerable uncertainty in projecting the country's tritium needs 13 years from now. Therefore it is important to assess the flexibility of the candidate technologies in response to production goal changes. There may be either higher or lower tritium requirements in the future and the date for initial production may be either pushed forward or delayed. In this connection, we make the following observations:

- The actual construction time of APT, assuming there exists an approved system design and a completed PEIS, is paced by the time required to build the accelerator, which is about 5 years. We believe, on technical grounds alone, that APT could meet the currently set requirement of beginning tritium production by the year 2005.

- For lower tritium requirements, APT system costs will decrease, primarily due to reduced electric power requirements.

- APT can operate to produce tritium at lower goal quantities by reducing either the power or the running time of the accelerator.

The difference between this panel's positive recommendation to include the APT in the PEIS and the conclusions of the ERAB report of February 1990 can be attributed primarily to the following changes:

- The significant reduction in goal quantities for tritium which correspondingly reduces the cost of the power for the APT. Cost of course will be a major factor in evaluating APT as an alternative to a new production reactor.
- The delay in the date for the ROD, allowing more time to answer basic technology questions about the target design and beam cycling.
- Advances in understanding of accelerator issues and progress in accelerator technology development.
- Continued development of target concepts and the appearance of an attractive new type of target (the LANL ^3He target).

Specific program recommendations for the accelerator and target subsystems are made in the corresponding technical sections of this report. The Panel's R&D recommendations are primarily focussed on engineered safety features. Speedy accomplishment of the needed R&D is crucial and we strongly encourage the National Laboratories to pool their APT efforts into a cooperative program, especially on the target design, where most of the uncertainties reside.

A MEMORANDUM

The Secretary of Energy
Washington, DC 20585

December 24, 1991

MEMORANDUM FOR DR. WILLIAM HAPPER, ST-1

SUBJECT: FEASIBILITY STUDY OF ACCELERATOR PRODUCTION OF TRITIUM

I request that you conduct a review of the feasibility of accelerator production of tritium (APT).

The review is to evaluate the feasibility and practicality of producing goal quantities of tritium using particle accelerator technology. It should be based on and include analyses of existing proposals and studies and on detailed briefings from accelerator proponents and others. The analyses should address, but not be limited to, design and engineering challenges, economics, environment, and safety.

On November 1 my decision to incorporate the New Production Reactor's Environmental Impact Statement into the broader environmental study on modernization of the Department's nuclear weapons complex was announced. This decision was made in light of President Bush's dramatic announcement to further reduce the Nation's quantity of nuclear weapons.

Considering these recent developments, I feel it is appropriate to further review and evaluate the state of accelerator technology as it applies to the production of tritium.

Please complete this APT review expeditiously and provide me with a report of your findings and recommendations by February 21, 1992.

James D. Watkins
Admiral, U.S. Navy, (Retired)

B PANEL MEMBERS

Sidney Drell - Chaiman
Deputy Director
Stanford Linear Accelerator Center

Richard J. Briggs
Deputy Director
SSC Laboratory

Robert S. Brodsky
President
Nuclear Power Technology, Inc.

Curtis Callan
Professor of Physics
Princeton University

Rudolph J. Dietz
Consultant

Douglas Eardley
Professor of Physics
U. C. Santa Barbara

David Hammer
Director
Laboratory of Plasma Physics
Cornell University

James R. Hilley
Consultant

John W. Landis
Director and Senior Vice President
Stone and Webster Eng. Corp

James E. Leiss
Consultant

Richard Muller
Professor of Physics
U. C. Berkeley

Burton Richter
Director
Stanford Linear Accelerator Center

Malvin Ruderman
Professor of Physics
Columbia University

Sam Trieman
Professor of Physics
Princeton University

David A. Ward
Consultant